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Comparison of dosimetry methods for panoramic radiography: Thermoluminescent dosimeter measurement versus PC-based Monte Carlo method calculation

파노라마방사선검사의 선량 측정: 열형광선량계 측정법과 컴퓨터 기반의 몬테 카를로법의 비교

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ABSTRACT

Comparison of dosimetry methods for panoramic radiography: Thermoluminescent dosimeter measurement versus PC-based Monte Carlo method calculation

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Purpose

The purpose of this study was to evaluate the patient radiation dose of panoramic radiography calculated with PC-based Monte Carlo software (PCXMC) compared to thermoluminescent dosimeter (TLD) measurement. Appropriate input values for dose-determining factors in PCXMC were also proposed.

Materials and Methods

Tissue-absorbed doses and the effective dose from panoramic radiography were measured with TLD and with PCXMC under various conditions. The calculated PCXMC doses were compared with those measured with TLD.

Results

The effective doses calculated with PCXMC showed differences by 9.6% to 51.2% compared to the doses measured with TLD. Reference points on Y and Z-axis were the sensitive factors when calculating effective dose. The differences between the highest and the lowest organ dose were 0.32 and 0.10 mGy respectively for PCXMC calculation and TLD measurement.

Conclusion

The effective dose calculated with PCXMC was mostly higher than the dose measured with TLD, and the absorbed doses varied by organ more severely in the PCXMC calculations than in the TLD measurements. The effective dose obtained from PCXMC calculations was dependent on input values for dose-determining factors. Standard values for each dose-determining factor required

to apply PCXMC to panoramic radiography were suggested in this study.

Key words: Monte Carlo Method, Radiographic, Panoramic, Thermoluminescent Dosimetry

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Contents

I Introduction

1. Background of the study

X-ray was discovered by W.C. Röentgen in 1895. Due to this evolutional discovery, medical field progressed remarkably with understating internal structure of human body. In present time, X-ray gives benefit to human life as it is contributing to both diagnosis and treatment of pathologic condition of human body. Since the discovery, diagnostic technology using X-ray has been advanced and its usage in medical field has been increased rapidly. Along with, the patient exposure dose from diagnostic X-ray became an issue. Awareness is growing that radiation from diagnostic X-ray contributes increasing proportion of overall population dose.[1] Considering harmfulness of radiation dose to human body as it increases biological toxicity, it is important to control radiation dose from diagnostic tools. Most of X-ray examinations, especially dental radiography, exposes radiation dose far below the level revealing deterministic effects. However, any kind of X-ray increases risks of stochastic effects which give raise to manifestation of tumor or hereditary effect. Thus, dose evaluation and managing suitable exposure dose are essential to keep

diagnostic X-ray dose as low as possible while still producing reasonable image quality.

For evaluating radiation dose of various type of diagnostic tools, standardized method with appropriate unit is required. Radiation dose influencing human body can be evaluated as an effective dose. Jacobi[2] introduced this concept of "effective dose" in 1975; *The effective dose is the mean absorbed dose from a uniform whole-body irradiation that results in the same total radiation detriment as from the nonuniform, partial-body irradiation in question.* In other word, this value is obtained considering interaction between body organ and X-ray, tissue weighting factor and the type of radiation energy. Thus, effective dose can be a scale indicating biological injury and possible health risk to people from the certain diagnostic modality.[1,2]

2. Recent trend in the dosimetry in dental field

In the dental field, panoramic radiography is a routine diagnostic X-ray tool. Its effective dose is lower than other types of X-ray examination such as cone beam computed tomography (CBCT). Shin et al.[3] studied the effective dose of panoramic radiography and CBCT. The resultant effective dose of panoramic radiography was

67−21 times lower than that of CBCT. Dental radiography is known as one of the most frequently performed radiological procedure.[4] Among dental radiography, the frequency of the panoramic radiography is higher than other types of modalities. Panoramic radiography is the most routinely performed for new patients as well as recall check patients in dental clinics. Also, the frequency of the examination has been increased drastically. Panoramic radiographic examination has been increased up to 112.6% in 2009 compared to 2006 in Korea[5]. Moreover, its radiation field exposes the head and neck area, including the lenses of the eyes, salivary glands, and thyroid gland. White[6] reported that when assuming effective dose of panoramic radiography as 6.7 μSv, the estimation risk of fatal malignancy was 0.21×10^{-6}. He also mentioned that due to the pathway of rotation center in panoramic radiography, higher dose could be exposed to mandible and parotid glands. Thus, it is important to evaluate the effective dose of panoramic radiography.

There are several methods which were used by researchers to achieve practical effective dose up to present time. Dosimeters and techniques for interpretations are required for the procedure. It is required to standardize dose measurement procedures since

effective dose were greatly varied depending on measurement method.[1] Also, different models and types of panoramic radiography are performed under different exposure condition with respective geometry and this may induce difficulty in assessment of effective dose. Shin et al.[3] reported that the effective dose of panoramic radiography was 6.39 μSv for CRANEX 3+ CEPH. In another study conducted by Lee et al.[7] the effective dose of film-based machine, ProMax and ProlineXC (indirect) were 37.8 and 27.6 μSv, respectively. The values were 8.9 and 15.6 μSv respectively for OP100 and ProlineXC (direct).

Effective dose can be measured through various methods. Among them, TLD and human body phantom have been widely used.[7-9] The use of TLD chips with a human body phantom is, however, a sophisticated and difficult process. Several other dosimetry methods were developed to supplement inconvenience of TLD. Study for replacing TLD with optically stimulated luminescence dosimeter (OSLD), which is used mostly for monitoring occupational radiation, has been conducted.[10] Metal-oxide semiconductor field-effect transistor (MOSFET) is also recently applied to dose measurement in diagnostic radiography, such as CBCT[11]. Yet there are no studies on radiation dose measurement

with MOSFET in panoramic radiography, recent study reported that MOSFET is comparable to TLD in low-dose dental radiography.[11] Software calculation adopting the Monte Carlo method is another way to measure the effective dose. This calculation simulates the pathway of X-ray photons as they interact with organ tissue. The personal computer-based Monte Carlo software program (PCXMC) is one of the most frequently used programs for software calculation of patient doses in X-ray examinations and is commonly used for chest radiography or computed tomography (CT).[12]

Compared to TLD measurement, the PCXMC software calculations are easier to perform with substantial accuracy.[12-14] The calculation simply requires inputting the exposure dose and the proper value for dose-determining factors. Exposure dose gives information about the amount of X-ray photon and dose-determining factors help to simulate behavior of each X-ray photon in the software.

However, for the calculations for panoramic radiography, it is difficult to determine some dose-determining factors which are closely related to the machine geometry. In other words, those factors are complex in panoramic radiography due to the complicated geometry of the system, as it is a combination of scanography and tomography. Unlike cephalometric or chest

radiography, the rotational center of panoramic radiography changes position continuously during X-ray exposure. Furthermore, neither the size of the X-ray beam nor the central ray passage is accurately known. These uncertainties raise difficulties in determining the input values for the Monte Carlo method. Therefore, the appropriate input values for the application of the software calculations to panoramic radiography must be determined. Then, the effective dose from the calculations should be compared to that from the TLD measurements, which has been widely used method until recently.

3. Purpose

In the present study, our goal was to evaluate the effective dose by software calculations with PCXMC and then to compare this with the experimental value from TLD measurements. In the process of the calculations, appropriate input values for dose-determining factors in PCXMC were also proposed.

II Materials and Methods

The equipment used was a panoramic imaging machine, OP-100 (Instrumentarium Dental, Tuusula, Finland). Exposure parameters were set at 73 kVp, 10 mA, and 17.6 seconds, which were the optimized parameters according to the user's manual of the machine for imaging adult males in the department.

1) TLD measurement

TLD measurement mostly followed the process described by Ludlow et al.[15-17] The measurement was conducted with TLD-700 (LiF 7: Mg, Ti) chips placed in the head and neck of a RANDO phantom (Nuclear Associates, Hicksville, NY). In total, 60 chips were embedded in 20 phantom sites, with three chips embedded in the same site to minimize internal chip error. The phantom sites are listed in Table I. Before the exposure, the internal error of each chip was measured and only chips with an error of less than 15% were used. After calibration of the TLD chips, panoramic radiography examination was conducted. The exposure was repeated three times to minimize error due to the low dosage of the examination.

The TLD chips were left in place for 24 hours, then read with a RADOS RE-1 reader (Rados Technology, Turku, Finland). The average absorbed dose of the chips at each site was obtained in micrograys (μGy). From these values, an equivalent dose (H_T) in microsieverts (μSv) was calculated using the percentage of the respective organ irradiated (Table II).[15-17]

The bone marrow equivalent dose was calculated for the calvaria, mandible, and cervical spine. The distribution of active bone marrow for an adult body is known to be 11.8% for the calvaria, 1.3% for the mandible, and 3.4% for the cervical spine.[18] For the bone surface dose, bone marrow dose was multiplied by bone/muscle mass energy absorption coefficient ratio (MEACR) according to the data from the National Bureau of Standards handbook No. 85.[18] The highest tissue absorbed dose was multiplied by the percentage of skin irradiated to obtain the skin equivalent dose.[17]

The effective dose (μSv) was obtained by the following equation: ΣWt X H_T, where Wt is the tissue weighting factor. The tissue weighting factors for head and neck tissue recommended by the International Commission on Radiological Protection (ICRP) 2007 are summarized in Table III.[19]

2) PCXMC calculation

PCXMC20Rotation, a supplemental program of PCXMC 2.0 (STUK, Helsinki, Finland), was used for the software calculation of effective dose. The dose-determining factors required by the software as input values are the patient age, X-ray voltage, filtration, input dose, number of projection angles, oblique angle of the central ray, focus-to-reference distance (FRD), X-ray beam height and width, and the reference point on the X, Y, and Z-axes.

The following factors were input according to the software and panoramic machine's manual: 30 years for the patient age, 73 kVp for the X-ray voltage, and 2.5 mmAl for the filtration. For the input dose value, the dose-area product (DAP) value was measured using a DAP meter (Diamentor M4-KDK, PTW, Freiburg, Germany). The DAP value was measured three times and corrected with the coefficient for the temperature and atmospheric conditions. The values were then averaged to minimize the measurement error. Those undefined factors for panoramic radiography were as follows: a) the number of projection angles, b) the oblique angle of the central ray, c) the reference point on the X, Y, and Z-axes (X_{ref}, Y_{ref}, Z_{ref}), d) the FRD, e) the X-ray beam height, and f) the beam width. The current study suggested the input values for the above

factors as detailed below.

a) *Number of projection angle.* Because the X-ray beam is continuously on as the source rotates, the projection angle varies within the total rotational angle of 240° which was confirmed by manufacturer. For the software calculation, the total rotational angle should be divided into a regular series of small angles. Thus, the range from 0° to 240° was divided into 1°, 5°, and 10° increments and the number of projection angles was given as 241, 49, and 25, respectively. It was assumed that the smallest angle would be the most accurate in modeling the continuous beam; thus 241 (1°) was set as the preferred value.

b) *Oblique angle of the central ray.* Vertical angle of central ray in panoramic radiography slightly goes upward, called oblique angle in the software. It is known as negative value between −5 and −10°. An oblique angle of −8° was given as the preferred value and −5 and −10° were also input.

c) *Reference point on the X, Y, and Z-axes.* The reference point is defined as the point where the central rays from all projection angles intersect. The software roughly depicted this point as 0, −5,

82 cm on the X, Y, and Z-axes, respectively (Figure1).[20] As the software phantom produces a very approximate value for the point on the postero-anterior and supero-inferior directions, additional input values of 0 and -3 cm for the Y-axis and 80, 84, and 86 cm for the Z-axis were given.

d) *FRD.* The FRD is defined as the distance from the X-ray focus to the reference point. The reference point was defined above and this point was assumed as equivalent to the point on the rotational axis of the panoramic machine. X-ray source rotates around fixed vertical axis in the machine, even though the distance between dental arch and the source changes during the examination. The distance between X-ray source and this rotational axis of the machine was measured manually with a digital caliper. The measured value of 35 cm was given as the preferred value, and 33 cm and 37 cm were additionally given in consideration of error in manual measurement.

e) *X-ray beam height.* The X-ray beam height is defined as the height of the beam when it reaches the reference point. Equation (1), with the manual measurement values of collimator height (CH) = 3.78 cm, collimator width (CW) =0.09 cm, focus-to-collimator distance (FCD) = 13.0 cm, and FRD = 35.0 cm, was used to

calculate a beam height of 10 cm (Figure 2). The calculated value of 10 cm was given as the preferred value, while values of 9 cm and 11cm were additionally input in consideration of any manual measurement errors.

$$BH = \frac{CHXFRD}{FCD} \text{ , (1)}$$

$$BW = \frac{CWXFRD}{FCD} \text{ , (2)}$$

f) *X-ray beam width.* The beam width, like the beam height, can be defined as the width of the beam at the reference point. It was calculated as being equal to 0.2 cm based on the equation (2) and the measured values given above (Figure 1). Values of 0.1 and 0.3 cm were also given in consideration of measurement error.

The software calculations were performed repeatedly with different input values for one factor and while all other factors where held at their fixed preferred values. For resulting effective doses, the mean value and the difference between the highest and the lowest value in accordance with varied input values were obtained for each dose-determining factor.

3) Data analysis

The difference between the mean effective dose of each dose-determining factor from PCXMC calculation and the value from the TLD measurement was obtained. For calculating the difference, the absolute differences between the TLD and PCXMC measurements were divided by the TLD measurement. According to Toivonen et al,[21] the difference below 25% indicated excellent agreement between both methods. The difference between 25% and 50% was defined as good and the value between 50% and 75% was moderate in agreement. The difference over 75% was classified as poor in agreement, The organ dose of each dose-determining factor from PCXMC was averaged to make a comparison with the TLD measured value. The difference between the highest and the lowest organ dose from PCXMC was compared with that from TLD. Standard values for dose-determining factors to use with PCXMC were suggested, taking the above analysis into consideration.

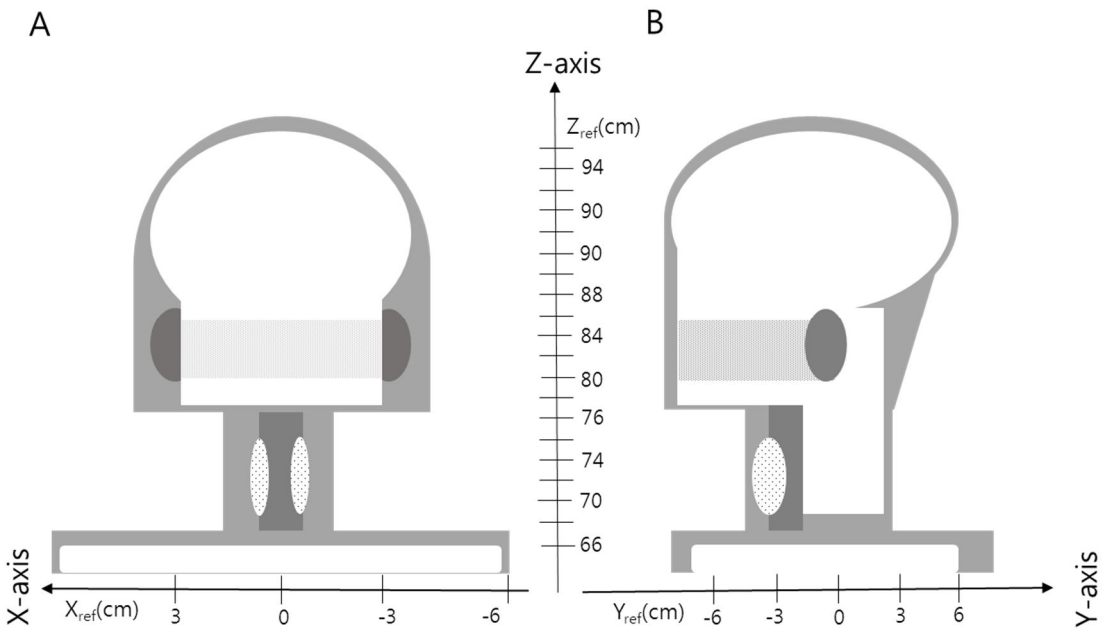

Fig 1. X-, Y-, and Z-axis on the virtual phantom used in PCXMC. The X-axis crosses right to left, the Y-axis posterior to anterior, and the Z-axis inferior to superior. Reference points on each axis were the location through which the central ray of panoramic radiography passes.

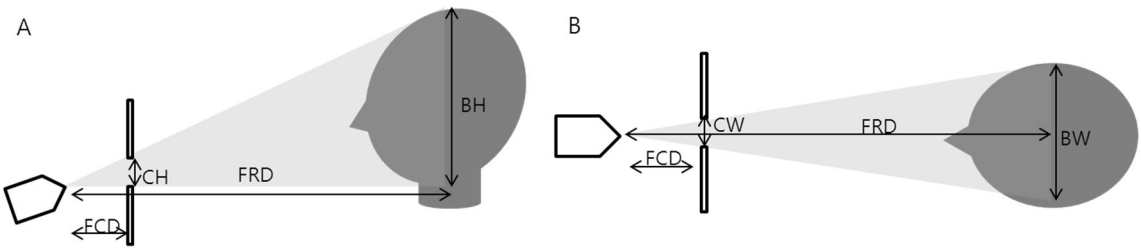

Fig 2. Schematic of X-ray beams in panoramic geometry in (A) sagittal and (B) axial view. (CH = Collimator height, CW = Collimator width, BH = Beam height, BW = Beam width, FCD = Focus-to-collimator distance, FRD = Focus-to-reference distance)

Table I. Location of TLD chips in the phantom

Phantom location (level of TLD location)	TLD ID
Calvaria anterior (1)	1
Calvaria left (2)	2
Calvaria posterior (4)	3
Midbrain (3)	4
Pituitary (4)	5
Right lens of eye (4)	6
Left lens of eye (4)	7
Right ethmoid sinus (5)	8
Left maxillary sinus (5)	9
Right parotid (5)	10
Left parotid (5)	11
Right ramus (6)	12
Left posterior of neck (6)	13
Right submandibular gland (7)	14
Left submandibular gland (7)	15
Center sublingual gland (7)	16
Oropharyngeal airway, center of the cervical spine (7)	17
Left lateral side of neck (9)	18
Left thyroid (9)	19
Right thyroid, esophagus (9)	20

Table II. Percentage of organ irradiated in radiographic examination of head and neck area[15-17]

	Fraction irradiated	TLD ID
Bone marrow*		
Mandible	1.3%	12
Calvaria	11.8%	1, 2, 3
Cervical spine	3.4%	17
Thyroid	100%	19, 20
Esophagus	10%	20
Skin	5%	
Bone surface†	16.5%	
Mandible	1.3%	12
Calvaria	11.8%	1, 2, 3
Cervical spine	3.4%	17
Salivary glands		
Parotid	100%	10, 11
Submandibular	100%	14, 15
Sublingual	100%	16
Brain‡	100%	4, 5
Remainder tissue‡		
Lymphatic nodes	5%	14, 15
Muscle	5%	10, 11
Extrathoracic airways	100%	17
Oral mucosa	100%	12
Pituitary	100%	5
Eyes	100%	6, 7

*Bone marrow = 0.013 x mandible + 0.118 x calvaria + 0.034 x cervical spine[18]
†Bone surface = bone marrow dose x bone/muscle mass energy absorption coefficient ratio (MEACR), MEACR = −0.0618 x 2/3 kVp + 6.9406.[18]
‡2007 recommendation of the ICRP.[19]

Table III. Tissue weighting factors (W_T) for organs in the head and neck region from ICRP 2007 recommendation[19]

Tissue	W_T
Bone marrow	0.12
Esophagus	0.04
Thyroid	0.04
Bone surface	0.01
Brain	0.01
Salivary glands	0.01
Skin	0.01
Remainder tissue*	0.12
Lymphatic nodes	
Muscle	
Oral mucosa	
Extrathoracic region	

* Among adrenals, extrathoracic region, gall bladder, heart kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus and uterus/cervix, following tissues were included for calculation of maxillofacial dose; lymphatic nodes, muscle, oral mucosa and extrathoracic region.

III Results

The effective dose of panoramic radiographic examination in a male adult was 7.153 μSv when measured with TLD. With PCXMC, the results varied depending on the different input values of the dose-determining factors. The effective dose differences between TLD and PCXMC were also obtained by percentage and are presented in Table IV. Two effective doses calculated by PCXMC were excellent in agreement with the value from TLD. Nineteen PCXMC calculated results were good agreement with TLD while 1 showed moderate agreement. No result from PCXMC showed poor agreement with TLD. For each dose-determining factor of PCXMC, the mean effective dose and the difference between the highest and the lowest dose were described in Table V.

Changes in the input value for the X-ray beam width, followed by the FRD, resulted in the least change to the effective dose, while Y_{ref} followed by Z_{ref} were the most sensitive factors and produced the largest changes in effective dose depending on the input value. Organ doses for different values of Y_{ref} and Z_{ref} are compared in Figure 3.

Among the organs of the head and neck region (Figure 4), the salivary gland showed the highest absorbed dose in both TLD and

PCXMC measurements for all input values. The absorbed dose for bone marrow showed the lowest value in the TLD measurements, while the esophagus showed the lowest value in the PCXMC calculations. The absorbed doses varied by organ more severely in the PCXMC calculations than in the TLD measurements. The use of PCXMC resulted difference of 0.32 mGy between the highest (salivary gland) and the lowest (esophagus) organ dose. TLD gave a difference of 0.10 mGy between the highest (salivary gland) and the lowest (bone marrow) organ dose.

Table IV. Effective dose (μSv) calculated with PCXMC for different input values

	Projection angle (°, number)			Oblique angle (°)			Focus-to-reference distance (cm)			Beam width (cm)		
Input value	1, 241	5, 49	10, 25	−5	−8	−10	33	35	37	0.1	0.2	0.3
Effective dose	9.388	9.401	9.439	9.403	9.388	9.357	9.402	9.388	9.386	9.382	9.388	9.376
Difference (%)*	31.3	31.4	32.0	31.5	31.6	30.8	31.4	31.3	31.2	31.2	31.3	31.1

	Beam height (cm)			Y_{ref} (cm)			Z_{ref} (cm)			
Input value	9	10	11	0	−3	−5	80	82	84	86
Effective dose	9.647	9.388	9.126	6.423	10.82	9.388	9.228	9.388	9.074	7.836
Difference (%)*	31.4	31.3	27.6	10.2	51.2	31.3	29.0	31.3	26.9	9.6

* Percent difference = $\left|\frac{TLD\ effective\ dose - PCXMC\ effective\ dose}{TLD\ effective\ dose\dagger}\right|$ x 100

† TLD effective dose = 7.153 Sv

Table V. Mean effective dose and the difference between the highest and the lowest dose calculated using PCXMC.

	Mean (μSv)	Difference (μSv)
Projection angle (1°, 5°, 10°)	9.409	0.051
Oblique angle (−5°, −8°, −10°)	9.383	0.046
FRD* (33 cm, 35 cm, 37 cm)	9.392	0.016
Beam height (9 cm, 10 cm, 11 cm)	9.305	0.521
Beam width (0.1 cm, 0.2 cm, 0.3 cm)	9.382	0.012
Z_{ref}† (80 cm, 82 cm, 84 cm, 86 cm)	8.882	1.552
Y_{ref}‡ (−5 cm,−3 cm, 0 cm)	8.876	4.395

* Focus−to−reference distance
† Yref = reference point on antero−posterial axis,
‡ Zref = reference point on supero−inferior axis

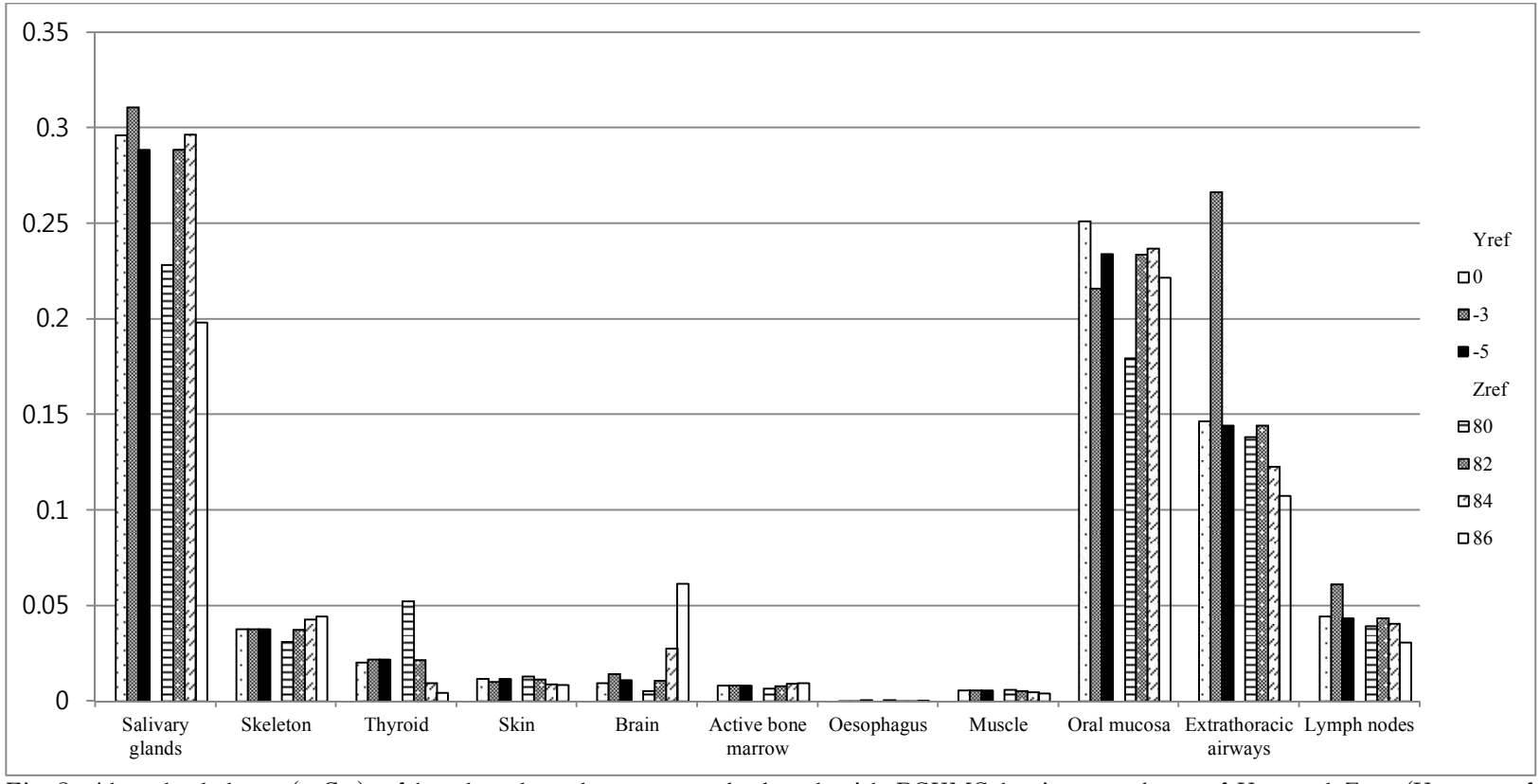

Fig 3. Absorbed dose (mGy) of head and neck organs calculated with PCXMC by input values of Y_{ref} and Z_{ref}. (Y_{ref} = reference point on antero-posterial axis, Z_{ref} = reference point on supero-inferior axis).

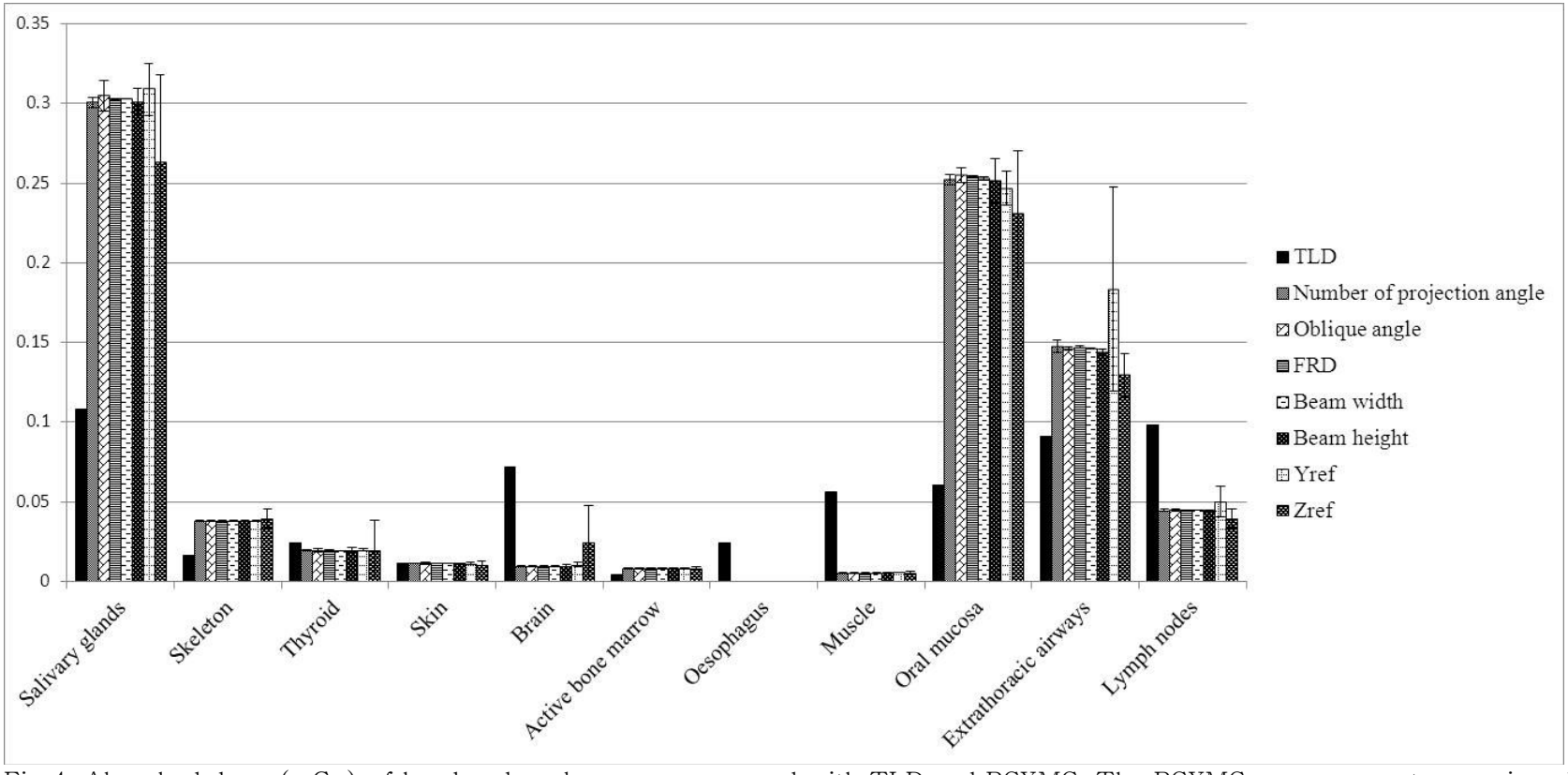

Fig 4. Absorbed dose (mGy) of head and neck organs measured with TLD and PCXMC. The PCXMC measurements are given by the dose-determining factor with the mean value and standard deviation shown. (TLD = Thermoluminescent dosimetry, FRD = Focus-to-reference distance, Y_{ref} = reference point on antero-posterial axis, Z_{ref} = reference point on supero-inferior axis)

IV Discussion

The Monte Carlo calculation is known as a convenient and accurate method to predict effective doses in the medical field.[12-14,22] Khelassi-Toutaoui et al.[12] reported that PCXMC showed a relatively high correlation with TLD measurements in organ doses compared to PREPARE (Oak Ridge National Laboratory, Tenessee, United States), another dose-calculation software. However, up to now the application of PCXMC has not been widely accepted for evaluating the radiation doses for panoramic radiography. The present study attempted to evaluate the PCXMC calculation method for patient dose compared to TLD with a human body phantom, which has been the most common method for evaluating radiation doses of panoramic radiography up to the present.

The effective dose

The effective doses calculated with PCXMC for various input values are summarized in Table IV. All of the PCXMC-based effective doses were higher compared to TLD-based effective dose, considered to be the gold standard, except one. This result was consisted with several previous studies reporting that TLD measured radiation dose was lower than the value calculated with PCXMC.[14,20,23]

The differences between PCXMC-based effective doses and the TLD-based effective dose were ranging from 9.6% to 51.2% according to the input values of the dose-determining factors. Twenty one PCXMC calculated effective dose showed excellent to good agreement with the TLD measured value, while 1 showed moderate agreement. This means that PCXMC may calculate less precise effective dose depending on the input values for the dose-determining factors. Moreover, these factors correlated with each other in determining the overall dose for panoramic

radiography due to its complex geometry, unlike other X-ray examinations such as cephalography or intraoral radiography. Thus, careful determination of the value for each dose-determining factor is necessary to simulate the physical conditions. The difference in resulting effective doses was highest for variations in the Y_{ref} values. This was most likely due to the change in the affected organs with the shift in the beam coverage area. The extrathoracic airways, esophagus, and salivary glands are located posterior to the dental arch. These organs showed a lower organ dose for Y_{ref} = −5 cm compared to Y_{ref} = −3 cm. While the oral mucosa, indicating the field of view in panoramic radiography, showed the highest absorbed dose when Y_{ref}=−5 cm. Thus, we recommended −5 cm as the standard value for Y_{ref}.

Z_{ref} was the second most sensitive factor in determining the effective dose. This phenomenon can be explained similarly to Y_{ref}. Koivisto et al.[20] reported that even a minor vertical change in the

head and neck position could cause significant changes in the absorbed and effective dose calculated with PCXMC. When the Z_{ref} value increases, the central ray, along with the beam coverage area, shifts to the top of the skull. In agreement with this, when the Z_{ref} value was increased in the present study, the brain dose increased while the thyroid dose decreased. Conversely, brain dose decreased while thyroid dose increased as Z_{ref} value decreased (Figure 3). The effective dose was altered mainly due to the inclusion or exclusion of the salivary gland, which is an organ with high tissue weighting factors. Among the different values, we suggest Z_{ref} = 84 cm as the standard value for PCXMC. With this value, the oral mucosa and salivary glands showed the highest absorbed doses.

In contrast to Z_{ref} and Y_{ref}, changes in the FRD had a relatively lower impact on the resulting effective dose. Due to the relatively large distance between the X-ray source to reference point,

minor measurement error in the FRD may be neglected. Because the distance between the dental arch and the X-ray source is not constant during rotation in panoramic radiography, adopting the FRD as measured from focus to rotational axis of the machine, as we did in the present study, would be simple and relatively accurate.

Variations in the input values for beam width also had a smaller relationship with the calculated dose. Regardless of the beam width, the exposed dose, DAP value, and total area exposed by the X-ray beam were constant. Thus, the effective dose was not greatly altered. In contrast, the effective dose decreased when the beam height was increased while maintaining a constant DAP value. When the beam height increased, the X-ray exposed area increased and consequently, the X-ray photons had a greater dispersion. Conversely, when the beam height is shorter the denser X-ray beam interacts with the organs. Thus the beam

height and width value were calculated based on the collimator size, FRD, and FCD [Equation (1), (2)]. The calculated values, 10 cm and 0.2 cm, are recommended as beam height and width standard values, respectively.

Podnieks and Negus[24] reported that the number of projection angles did not greatly affect the effective dose. They performed a PCXMC calculation of the effective dose for a cone beam CT with either 4 or 41 projections. The difference was only 7% on the upper abdomen region and 2% on the lower and middle abdomen regions. In the current study, the difference between the largest effective dose (which was obtained with an input value of 10 projections) and the smallest effective dose (with an input value of 241 projections) was only 0.051 μSv. Even though the difference was slight, there was a tendency for the effective dose to increase as the number of projections decreased. An input

value of 241 projections (1°) resulted in the effective dose closest to that of the TLD measurements. Additionally, Podnieks and Negus[24] reported that the organ doses were significantly different when the number of projections was changed. Thus, determining the value for the number of projection angles cannot be disregarded. We suggest an angle of 1° (241 projections) to simulate the continuous scanning beam of panoramic radiography.

In the case of the oblique angle, as it was reduced, the organ dose of the oral mucosa decreased. However, choosing different input values was not a strong factor in changing the effective dose. The effective doses did not vary as greatly as they did for Z_{ref} or Y_{ref}. We surmise that even though the oblique angle changed, the head and neck organs that are interacting with the X-ray beam did not significantly change because the same beam size, and Z_{ref} and Y_{ref} values were used. Thus the oblique angle might be varied between

−5° and −10°, and the median value of −8° was suggested in this study.

In summary, the following standard input values for each dose-determining factor were suggested in this study: number of projection angles = 241, oblique angle = −8° , FRD = 35 cm, beam height = 10 cm, beam width = 0.2 cm, Z_{ref} = 84 cm and Y_{ref} = −5 cm. The effective dose calculated with the suggested input values showed 26.9% of difference compared to the TLD measured value. This was slightly over the 25.0%, below which two values are in excellent agreement.[21] As illustrated in Figure 4, PCXMC overemphasized the absorbed dose of some organs, such as salivary gland or oral mucosa. Toivonen et al.[21] mentioned that computer calculation markedly overestimated some organ doses and overall, the discrepancy between the computer-based and TLD-based effective dose increased. In addition, the difference was still lower than that from previous researches. According to

the studies on the effective dose of CBCT, PCXMC calculated value was 157 μSv while TLD measured value was 98 μSv in the same CBCT model.[25,26] Other studies reported 131 μSv with PCXMC and 58.9 μSv (maxilla) and 96.2 μSv (mandible) with TLD-based method.[20,26] These results showed 40~60% of discrepancy between the PCXMC and TLD-based method.

All effective doses calculated from PCXMC were higher than those from TLD. Automatic spinal compensation (ASC) for panoramic radiography might be one of the contributing factors for this phenomenon. The OP-100 imaging machine in this study is programmed to increase the voltage when the X-ray source passes the spine to compensate for it and acquire a clear image of the anterior teeth. It is difficult to determine exactly when the voltage is rising. It is also difficult to input various voltages for a single exposure in the software. Thus, PCXMC simulated an X-ray beam with constant voltage, which is contrary to the physical

parameters. This may lead to disagreement between TLD and PCXMC in organ doses as well as in effective dose. Theoretically, as the voltage increases, more x-ray photons pass by the tissues. However, when the voltage decreases, photons scatter to adjacent tissue to be absorbed. Thus, low voltage in PCXMC may contribute to heightened organ doses as well as a heightened effective dose.

Organ absorbed dose

With respect to the organ doses, both TLD and PCXMC demonstrated similar behavior. For the organs measured as having a high absorbed dose with TLD, PCXMC also calculated higher values, while organs found to have a low dose by TLD also showed relatively lower values with PCXMC. In the head and neck region, the salivary and thyroid glands are known to be the most important organs in affecting the exposure dose. Because the salivary gland is located in the path of the central ray, the absorbed dose of the gland was the highest in both the TLD and

PCXMC measurements. Characteristically, the absorbed doses of the organs calculated by PCXMC fluctuated drastically, while the doses calculated with TLD remained relatively even across the different organs, as shown in Figure 4. The dose difference between the highest and the lowest organ dose from PCXMC calculation was three times larger than that from TLD measurement. There are several possible explanations for this difference. First, in the software calculations, the movements and interactions of the photons with the body organs were modeled theoretically only in perfectly fixed conditions. In reality, however, unexpected factors frequently exist, such as non-uniformity in X-ray voltage due to an uneven electric power supply. The software cannot actively account for such factors in simulating the photon-tissue interactions. Second, PCXMC calculations are conducted on a very simplified position of the organs in the phantom. The phantom used in PCXMC is based on the 1987

model of Cristy and Eckerman. The human body and organs were mapped in this phantom in rough and rudimentary ways, such as using simplified geometrical approximations like flat surfaces, cones, circles or ovals. This could raise the distortion in the organ doses. Zhang et al.[27] implicated that the phantom plays an important role in calculating dose of head and neck region. They conducted monte calro simulated dose calculation on different four phantoms with the same cone beam CT system. The resultant organ dose showed differences more than 100%. While, effective dose showed differences under 30%. Thus, the organ dose comparison between experimental measurements with TLD and software calculations with PCXMC might not be appropriate for panoramic radiography. In fact, ICRP 103 recommends phantom-based MRI or CT of an actual human body.[28] There are current efforts to develop more complicated and sophisticated phantoms such as voxel phantoms or hybrid phantoms.[29,30] For future

studies with more reliable organ dose calculations, software with a more developed phantom will be required.

V. Conclusion

The effective dose calculated with PCXMC was mostly higher than the dose measured with TLD, and the difference between the highest and the lowest organ dose from PCXMC was larger than that from TLD. The effective dose obtained from PCXMC calculations was dependent on input values for dose-determining factors. Standard values for each dose-determining factor required to apply PCXMC to panoramic radiography were suggested in this study.

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국문요약

파노라마방사선검사의 선량 측정: 열형광선량계 측정법과 컴퓨터 기반의 몬테 카를로법의 비교

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목 적

방사선검사의 선량을 측정에는 다양한 방법이 사용되고 있으며, 이 중 몬테카를로 기법을 이용한 계산 프로그램을 통해 선량을 도출하는 방법은 비교적 손쉬우며 정확한 유효선량을 얻을 수 있는 방법이다. 그러나 파노라마방사선장비는 그 원리가 복잡하여 프로그램을 통한 모사가 어렵고 입력값들의 결정이 단순하지 않기 때문에 아직 시도되지 않고 있다. 본 연구에서는 파노라마방사선검사의 유효선량을

몬테카를로 방법을 이용한 프로그램인 PC-based Monte Carlo method calculation (PCXMC)를 통하여 계산하고 이 값을 열형광선량계를 이용한 측정법과 비교하여 PCXMC 에 사용하는 표준입력값들을 제시하고자 한다.

방 법

PCXMC 프로그램을 이용하여 파노라마방사선검사 시 방사선노출량의 장기흡수선량과 유효선량을 계산하였다. PCXMC 로 선량을 결정하는데 영향을 주는 항목인 a) 회전각의 수, b) 수평각, c) 초점-모사체 거리, d) X 선속의 높이 및 e) 넓이, f) 중심 X 선이 지나는 X, Y, Z 축상의 기준값에 적절한 몇 개의 값을 선정하여 입력한 뒤 여러 개의 유효선량값을 도출하고 이 결과를 열형광선량계를 이용하여 계산된 흡수선량 및 유효선량값과 비교·평가 하였다.

결 과

TLD 측정값과 비교하였을 때 PCXMC를 통해 계산된 유효선량은 입력항목 기준값의 변화에 따라 9.6% 에서 51.2% 의 차이를 보였다. PCXMC 프로그램에서 Z축 및 Y축 상 기준값의 변화에 따라 도출된

유효선량이 가장 크게 변화하였으며, 초점-모사체 거리와 X선속의 넓이에 대한 입력값을 변화하였을 때, 유효선량의 변화가 가장 적었다. 가장 높은 흡수선량값을 보이는 장기와 가장 낮은 흡수선량값을 보이는 장기 사이의 값의 차이는 PCXMC에서 0.32 mGy, 열형광선량계에서 0.10 mGy로 PCXMC에서 큰 차이를 보였다.

결 론

PCXMC를 통하여 계산된 유효선량은 열형광선량계를 통해 측정된 값과 비교하여 대부분 높은 값을 보였다. 열형광선량계를 통해 측정된 장기흡수선량의 경우 장기 별로 비교적 고른 분포를 보인 반면, PCXMC에서는 각 장기 별, 큰 차이를 보였다. PCXMC를 통하여 얻은 유효선량은 선량결정항목들의 입력값에 의존하여 그 결과에 차이를 보였으며, 파노라마방사선검사에서 적용 가능한 적절한 입력값을 제시하였다.

주요어: 몬테카를로 시뮬레이션, 파노라마방사선검사, 열형광선량계
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